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Short-term development of Arctic beach system: Case study of wave control on beach morphology and sedimentology (Calypsostranda, Bellsund, Svalbard)

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Abstract: The objective of this research is to determine the impact of waves on the segregation of sediment within the area of its supply in the context of meteorological conditions. The research was conducted on a 4 km section of the shore of Calypsostranda (Bellsund, West Spitsbergen), shaped by waves such as swell, wind waves, and tides. Particular attention was paid to the diversity and variability of the surface texture within the intertidal zone. Meteorological measurements, recording of wave climate, as well as analysis of the grain-size distribution of the beach sediments were performed. Nearshore bathymetry, longshore drifts, episodic sediment delivery from land, as well as resistance of the shore to coastal erosion and direction of transport of sediments in the shore zone are important factors controlling shore development. Data show that wind waves contribute to erosion and discharge of material from the nearshore and intertidal zone. The research also shows that oceanic swell, altered by diffraction, reaching the shore of Calypsostranda contributes to better sorting of sediment deposited on the shore through washing it out from among gravels, and longshore transport of its finest fraction. The grain size distribution of shore sediments is significantly changed already during one tidal cycle. The degree of this modification depends not only on wave height and period but on the direction of wave impact. The shore of Calypsostranda can be regarded as transitional between high and low energy coasts.

Key words: Arctic, Spitsbergen, photogrammetric granulometry, sediment texture, impact of waves.

Introduction

The Arctic coastal environment is very sensitive to climatic changes, occurring extremely rapidly, particularly in the 21st century (Forbes *et al*. 2011; Nordli *et al*. 2014; Overduin *et al*. 2014; Isaksen *et al*. 2016; Strzelecki *et al*. 2017a, b; Nicolle *et al*. 2018). Climate changes and its consequences affect the dynamics of processes shaping the shore zone (St-Hilaire-Gravel *et al*. 2010, 2011; Zagórski *et al*. 2012; Atkinson *et al*. 2016; Strzelecki *et al*. 2018). One of the key factors that have a direct impact on the state of Arctic coasts is the protective role of sea ice. In recent years, the period of shore and coastal water icing has been shortened, which leads to an extension of the period of shaping the shore by the waves, especially stormy ones that are frequent in the winter season, thus increasing the dynamics of shore processes (Barnhart *et al*. 2014). According to Wojtysiak *et al*. (2018) storms along the west coast of Spitsbergen are now more frequent and last longer than in previous decades. Although most storms occur during the winter, storms occurring during spring and autumn are the most energetic, with significant wave height of up to 9.5 m (Wojtysiak *et al*. 2018), and have strong impact on the beach when the formation of shore ice is delayed (Rodzik and Zagórski 2009).

The coasts in the polar regions constitute about 34% of the coastline's length on the Earth, however only a small part of them has been thoroughly investigated (Lantuit *et al*. 2012). The changes taking place on the Arctic coasts were presented by many authors (John and Sugden 1975; Forbes *et al*. 2011; Overduin *et al*. 2014). The research was mostly carried out on the shores of Alaska (Jones *et al*. 2009; Wobus *et al*. 2011; Gibbs and Richmond 2015), Canada (McCann and Owens 1969; Solomon 2005; St-Hilaire-Gravel *et al*. 2010, 2011; Atkinson *et al*. 2016), Greenland (Kroon *et al*. 2010; Drewniak *et al*. 2014), Spitsbergen (Mercier and Laffly 2005; Sessford *et al*. 2015b; Strzelecki *et al*. 2017a; Zagórski *et al*. 2015) and Siberia (Lantuit *et al*. 2011; Ogorodov 2011; Ogorodov *et al*. 2013). Most of these investigations concerned areas characterized by the presence of permafrost. Few of them described specific polar coasts, which are not affected by direct influence of permafrost (Lantuit *et al*. 2012). Such areas include rocky coasts (Wangensteen *et al*. 2007; Strzelecki 2011; Świrad *et al*. 2017), river deltas (Lønne and Nemec 2004; Kowalska and Sroka 2008; Zagórski *et al*. 2013), and coasts built of unconsolidated material without visible ground ice, such as Calypsostranda or Isbjørnhamna on Spitsbergen (Zagórski 2011; Zagórski *et al*. 2015).

Only a few scientific papers discussed changes occurring during strong storms (Hume and Schalk 1967; Reimnitz and Maurer 1979; Zagórski 2011; Barnhart *et al*. 2014; Zagórski *et al*. 2015). Some authors suggested that storm surges do not leave long-lasting, visible traces on shores, and coasts can relatively rapidly return to their pre-storm state (St-Hilaire-Gravel *et al*. 2011). Others postulated that changes in the coastal zone depend only on the sediment type and on land processes, such as thermal erosion, thawing of permafrost, slope processes, and removal of sediments by rivers (Sessford *et al*. 2015a; Świrad *et al*. 2017).

For years, the study of waves on the Arctic seas has been limited only to the description of the prevailing wave climate that constitutes the background of other studies. Occasionally, individual storm episodes were mentioned (Reimnitz and Maurer 1979). Currently, wave monitoring is carried out in a relatively few places, which is insufficient because of large local variations in wave climate. Nevertheless, intensive development of numerical methods in recent years enabled modeling of wave impact with more valuable precision (Roland and Ardhuin 2014; Cavaleri *et al*. 2018; Herman *et al*. 2019). There are also attempts of conducting detailed research of the waves at the west coast of Spitsbergen and in the fjords (Wojtysiak *et al*. 2018; Herman *et al*. 2019).

The aim of this study is to determine the impact of waves on the beach surface, the sediment distribution and the efficiency of sediment transport along the beach under the circumstances of varying meteorological and sea-wave conditions.

Study area

The research was conducted on the Calypsostranda shoreline of Bellsund, connecting the system of internal fjords with the Greenland Sea (Fig. 1). The mapping of types of coast was already performed, processes acting/impacting the shore were identified, and their intensity and mutual relations were determined (Harasimiuk and Jezierski 1991). Since 1995, the shoreline changes of Calypsostranda has been regularly monitored. Studies have shown that despite long-term changes on multiannual time scales, short-term coastal advances or retreats may take place from year to year. According to Forbes *et al*. (2011) the southern shores of Bellsund can be regarded as a high-energy coast. In Calypsostranda, erosional coasts prevail. By contrast, the shores of the Recherchefjorden (Recherche Fiord) are not impacted by open sea waves, and thus represent a low-energy coast, mostly of accumulative character, and influenced by glacial and fluvioglacial processes. The shores of this fjord developed under the influence of glaciers that currently indirectly impact some of its parts; they can thus be regarded as a paraglacial coast (Forbes and Syvitski 1994; Mercier 2008).

The present study was conducted on a 4 km section of the shore of Calypsostranda, from Skilvika to Pocockodden (Fig. 1). Due to the influence of the warm West Spitsbergen Current and a long fetch, the Bellsund is predominantly ice free (Rodzik and Zagórski 2009). The sea ice cover that forms on nearshore waters during winter is quickly broken by waves and winds

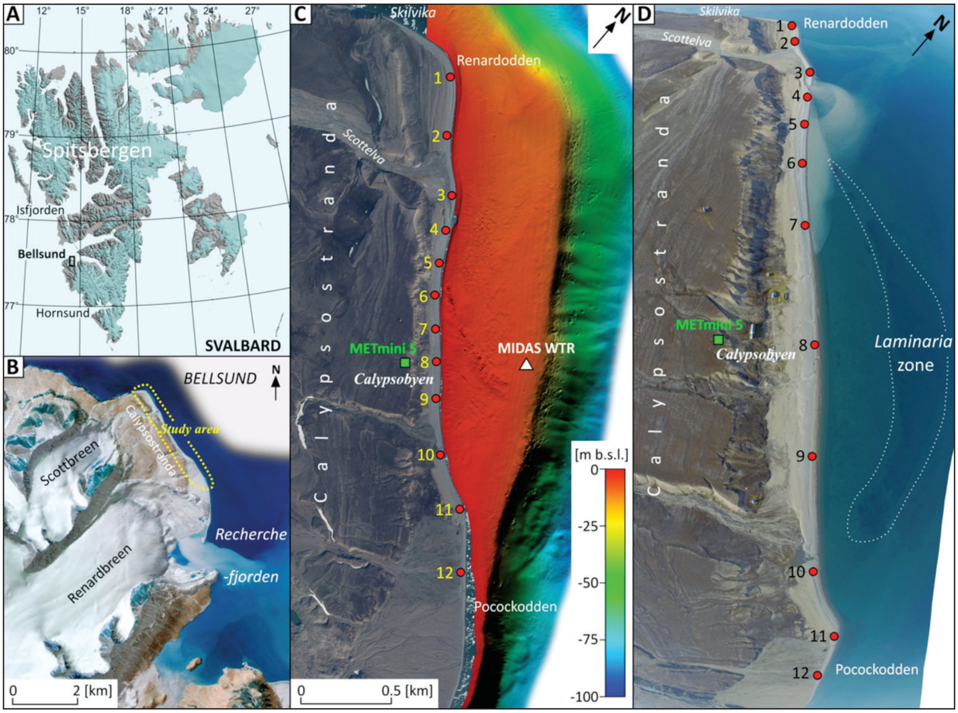

Fig. 1. Svalbard (**A**), the Bellsund area (**B**) after Orthophotomap (Zagórski 2005), location of measurement sites (**C**) according to Orthophotomap, air photo from 2011, Norwegian Polar Institute; bathymetric data from The Norwegian Hydrographic Service, and view of study area form an unmanned aerial vehicle (**D**). METmini 5, location of meteorological station, MIDAS WTR, location of MIDAS WTR Wave and Tide Recorder.

(Zagórski *et al*. 2013), however, shore ice is not formed here every year (Rodzik and Zagórski 2009). The maximal range of spring tides in summer season is 1.88 m (Zagórski 2011). The coastal landscape is composed of a series of raised marine terraces (Zagórski *et al*. 2013), adjacent to a complex of Neoproterozoic rocks assigned to the Bellsund Group superior unit (NPI 2016) scattered across the marine terraces. This succession is divided into the Bellsund phyllite Unit (phyllitye with clasts) and the Bellsund Group (diamictite) (Dallmann *et al*. 1990; Birkenmajer 2004). Along the coast (Calypsostranda), Paleogene sediments of the Calypsostranda Graben occur. The Graben is filled with rocks belonging to Calypsostranda Group (sandstone, siltstone, shale, coal) (Birkenmajer and Gmur 2010; NPI 2016). The bedrock comprises weakly cemented sandstones and shales (Palaeocene), covered by Quaternary glaciogenic deposits and marine gravels (Pękala and Repelewska-Pękalowa 1990; Harasimiuk and Jezierski 1991; Pękala *et al*. 2013). The shore is built of gravel sediments, and gently declines towards the north up to the slope of the main channel of the Bellsund (Moskalik *et al*. 2018) (Fig. 1C).

The NW part of the studied section of the coast constitutes the Skilvika cliff shore, which is the main source for sediments transported along the coast of Calypsostranda. The cliff with a height of approximately 25 m, undercut by waves, is modelled by intensive mechanical weathering and gravitational processes, *i.e*. slumps in the western part, and solifluction and landslide processes in the eastern part (Zagórski *et al*. 2012) (Figs 1 and 3).

The Renardodden (Renard Cape) at the boundary of Skilvika is located on an accumulative beach terrace of 1–6 m a.s.l. (meters above sea level) (Zagórski 2011). Convergence of longshore drift and bedload streams occurs in the region, increasing the intensity of accumulation processes (Harasimiuk and Jezierski 1991). The cape is built of sediment supplied by waves and longshore drifts from Skilvika and from Scottbreen (Scott Glacier) by Scottelva (Scott River) (Zagórski *et al*. 2008a, b; Zagórski *et al*. 2012). The sea floor bathymetry in front of the cape, alters the angle of wave impact, and further affects the intensity of the alongshore sediment transport. Older beach ridges, having a NW–SE orientation, are truncated by the modern storm rampart, which strikes WSW–NNE (Zagórski 2011; Zagórski *et al*. 2013).

Under calm sea conditions, the Scottelva forms an ephemeral delta at its mouth (Harasimiuk and Jezierski 1991). The mouth of the Scottelva is episodically closed by a storm ridge (Zagórski *et al*. 2013). A sediment delivery from land by the river is suggested by the widening of the storm ramparts and the entire beach zone in the region. Subsequently, the sediment delivered by the river is distributed along the shore due to wave action and alongshore drifts they cause (Fig. 3A).

The middle part of the shore of Calypsostranda is a typical accumulative gravel beach (Harasimiuk and Jezierski 1991; Zagórski 2011) (Figs 1 and 3). The southern part of the study area, the Pocockodden region, is occupied by an inactive outwash fan of the Renardbreen (Renard Glacier). The retreat of the glacier since 1960 and reduction in sediment supply to the fan resulted in its inactivation and further reworking of fan sediments by waves. As a result of coastal erosion, a boulder-dominated zone developed. It could be destroyed or recovered according to wave conditions prevailing in a given season (Zagórski *et al*. 2013).

Nearshore is formed by the rocky abrasive platform with a thin unconsolidated sediment covers gently dipping towards the fjord axe. This platform extends between Renardodden and Pocockodden, up to ~ 1 km wide and down to 10–15 m of water depth, limited by the steep edge of the Recherchefiorden (Moskalik *et al*. 2018) (Figs 1C and 3). In the area of Calypsobyen Palaeocene, rock outcrops and areas covered with seaweeds occur (NPI 2016) (Fig. 1D).

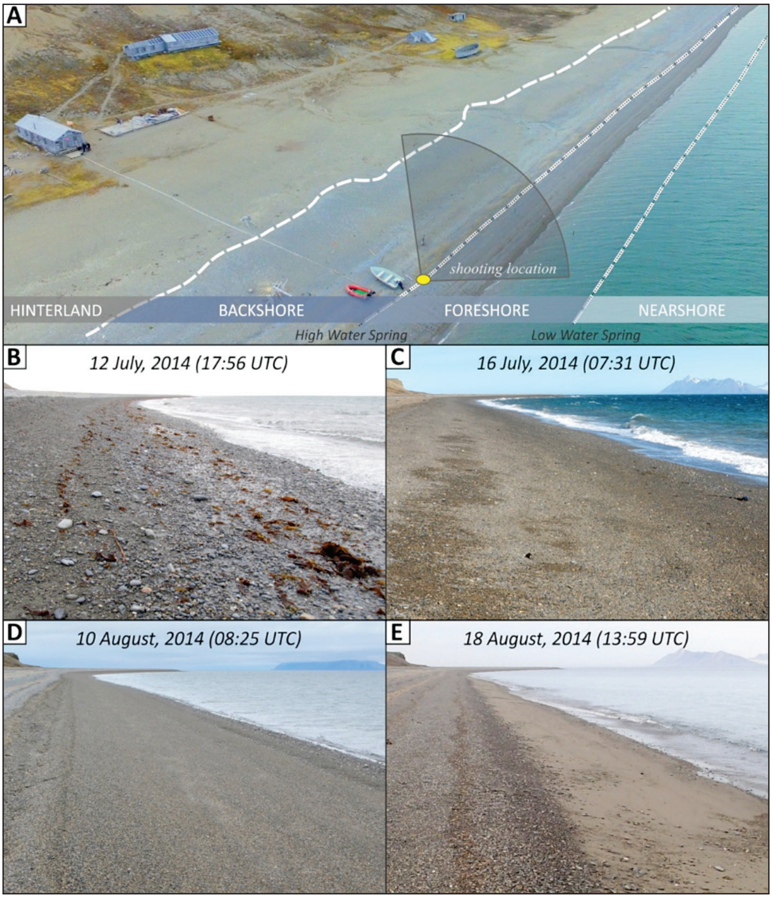

Fig. 2. Delimitation of coastal zone (**A**) and oblique image of the shore in selected shooting times at site 8 (**B–E**) at Calypsobyen.

Methods

Sedimentological data. — During each low tide, in the period from 8 July to 28 August 2014, oblique photographs of the intertidal zone at Calypsobyen (point 8: see Figs 1–3) were taken, recording changes in sediment deposited on the beach in the context of wave climate. Several pictures, showing various sediments (from sands to gravels), were selected and shown in Fig. 2. Moreover, at the end of the research, on 26–28 August, at 12 points (numbers 1–12) distributed along the shore of Calypsostranda, five series of vertical photographs of sediment deposited in the intertidal zone were taken during low tide, using a scaled frame of 40×50 cm. For each image, the grain-size distribution of the surface sediments was determined, using the Sedimetrics ® Digital Gravelometer software (Loughborough University

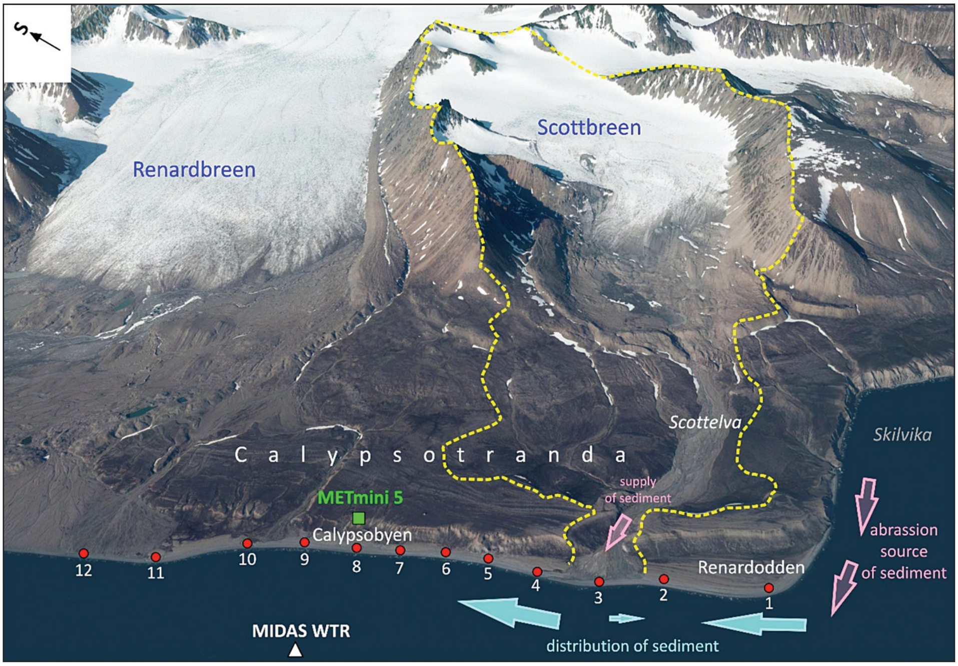

Fig. 3. 3D visualisation the Scottelva Catchment (yellow dotted line – boundary of the catchment; source: air photo from 2011, Norwegian Polar Institute). Arrows show the direction of material supply and its distribution in shore zone, METmini 5 – location of meteorological station, MIDAS WTR – location of MIDAS WTR Wave and Tide Recorder.

Enterprises Limited UK). This software was developed to measure river gravels (Rice and Church 1998; Butler *et al*. 2001; Sime and Ferguson 2003). However, in recent years, it has also been used for coastal sediments (Drewniak *et al*. 2014). Grain-size distributions were calculated according to the grid-by-number rule. This means that each grain is weighted based on its area, for details on algorithms and applications see (Graham *et al*. 2005a, b; Drewniak *et al*. 2014). For each site, cumulative frequency curves, mean grain size and sorting were calculated (Figs 7 and 8; Supplement 1). According to Graham *et al*. (2005a, b), image processing and grain measurement can fail if very fine sediment is present, because of poor image segmentation. Difficulties in distinguishing sand grains, which were inaccurately interpreted by the software, excludes some images from further analysis. These cumulative frequency curves are drawn in dotted line and points without filling on Figs. 7 and Supplement 1.

Oceanological data. — The record of waves and tides was conducted from 8 July to 27 August 2014 by MIDAS WTR Wave and Tide Recorder (MIDAS WTR), installed at a depth of 10 m at a distance of approximately 0.5 km from

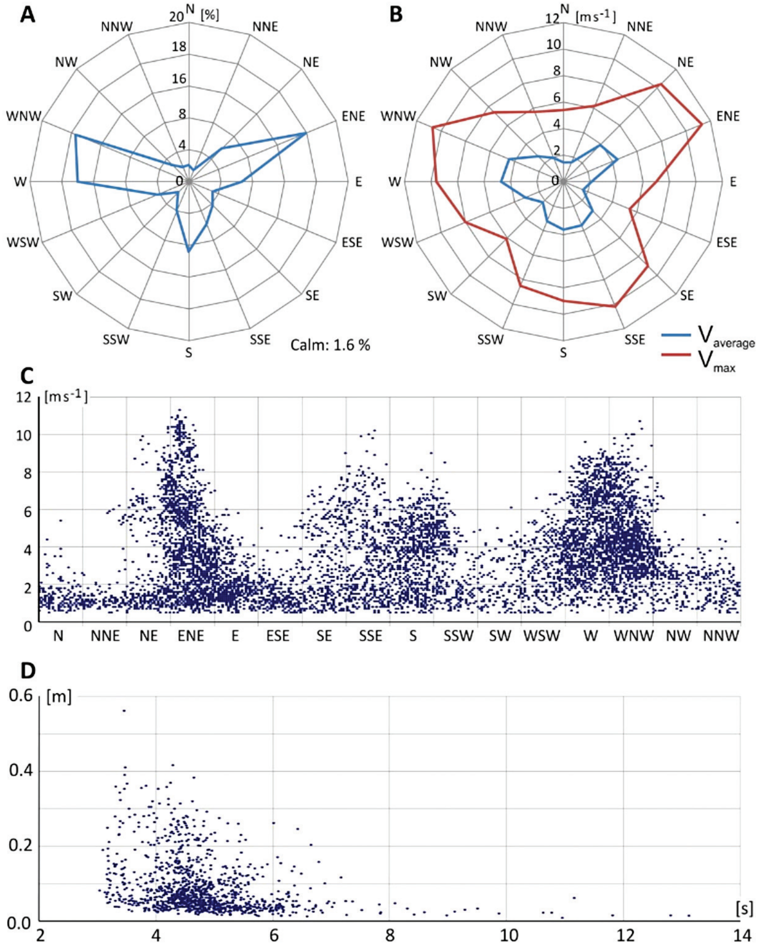

Fig. 4. Data from the summer season of 2014 in the Calypsobyen: (**A**) wind rose; (**B**) wind direction and speed rose; (**C**) correlation between wind direction and wind speed; (**D**) correlation between mean wave period and significant wave height.

the shore (Figs 1 and 3). The pressure data were recorded every hour for 4.5 min, with a time step of 0.25 s. Based on these time series, corrected for atmospheric pressure and tide, one-dimensional wave energy spectra were calculated (using the software accompanying MIDAS WTR) for the frequency range 0.015–1.203 Hz, with frequency resolution 0.031 Hz. These spectra provided the basis for the calculation of significant wave height (Hs) and the corresponding mean wave period (T). They reflect wave energy and length, determining the dynamics of shore processes, including the ability of the wave to lift and transport sediment, and affect the type and surface texture of sediments accumulated on the beach.

Weather data. — Meteorological measurements were conducted by an automatic meteorological station (Vaisala METmini 5; A-STER, Cracow Poland) with a 10-minute time step in the period from 8 July to 1 September 2014. The station was located on the flat surface of an elevated marine terrace, at a height of 23 m a.s.l., approximately 200 m from the shore (Fig. 1). The station was sheltered by mountains towards the west which causes underestimation of winds blowing from westerly directions, *i.e*. from Calypsobyen, as compared to the entrance to the fjord. The following standard meteorological measurements were conducted: temperature, air humidity, amount of precipitation, and wind direction and speed at a height of 7 m above ground level, using bowl anemometer (Mędrek *et al*. 2014) (Fig. 4). Data on wind directions permitted the determination of the direction of wave impact on the shore. In the majority of situations, waves in the study area are generated locally in Recherchefjorden. The direction of swell from the open sea usually differs from the local wave direction. Swell waves do not reach the shore directly because they are diffracted on subsequent capes, and propagate along the SW shore of Bellsund.

Shoreline change data. — Measurements of the shoreline on the study area were carried out twice a season (16 July and 14 August) after maximum spring tides by means of Differential Global Positioning System (DGPS, Leica system 500) with centimetre accuracy (Fig. 5). An ephemeral gravel ridge determining the tidal range was measured as the shoreline marker. Subsequently, data were analysed by means of DSAS (Digital Shoreline Analysis Tool), a supplement of ESRIs ArcGIS software (Thieler *et al*. 2009). DSAS uses a simple linear regression method to compute rates of change of shorelines, provided that a vector version of their shape exists. It furthermore generates transects that cross the shoreline at given intervals. The Net Shoreline Movement (NMS) method was used for computing the difference between the oldest and youngest shoreline at every transect (Thieler *et al*. 2009). Negative values represent shore erosion, while positive values represent sediment accumulation (Fig. 6).

Results

Wind conditions. — During the summer season of 2014, in Calypsobyen, W winds were recorded most frequently (25.7%; Fig. 4), while during summer seasons in years 1986–2011 wind from this direction usually accounted for 5–10% (Mędrek *et al*. 2014). This shows that the anemometric conditions of the 2014 season significantly differed from those in previous years. The contribution of winds from NE and E were also high (15.8% and 15.2%, respectively). Winds from N (3.8%) and SW (4.5%) were the rarest. The contribution of calm conditions amounted to only 1.6%. The highest average wind speeds

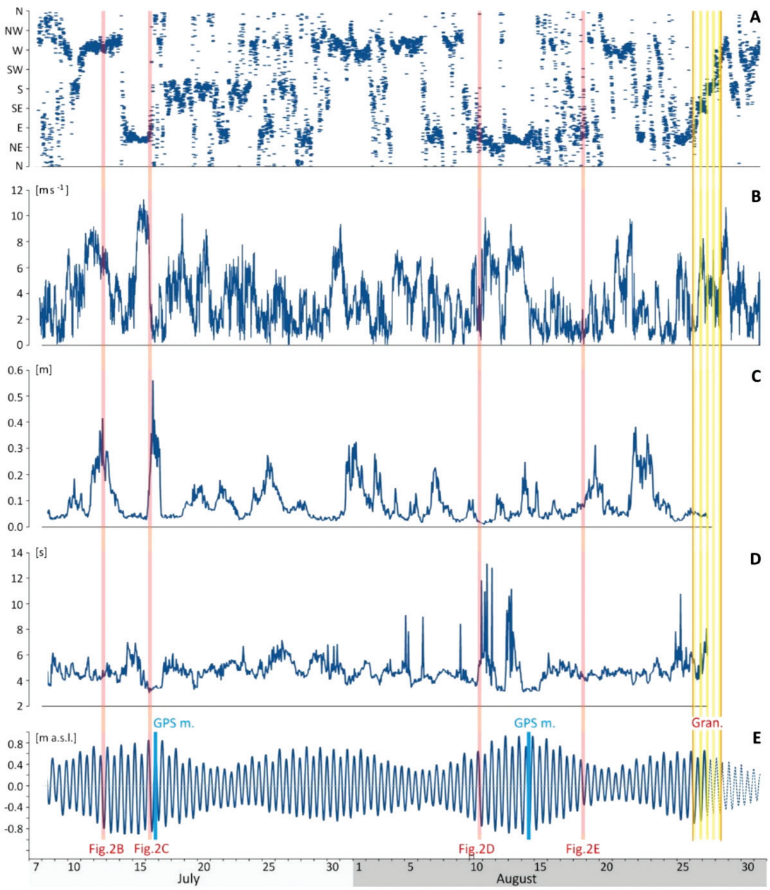

Fig. 5. Data from the summer season of 2014 in the Calypsobyen: (**A**) wind directions, (**B**) wind speeds, (**C**) significant wave height, (**D**) mean wave period, and (**E**) height of tidal waves; solid line – data from MIDAS WTR, dotted line – simulation data. GPS m. – the date of GPS measurements of shoreline (see Fig. 6), Gran. – the date of taken of images (see Figs 7 and 8).

(> 4.5 m/s) occurred from W and NE, whereas the lowest average speed (1.5 m/s) characterised northerly winds.

At the beginning of the measurement season, wind speeds were low and exceeded 8 m/s only on 12 July (Fig. 5). The highest wind speed in the summer season 2014, 11.3 m/s, was recorded on 16 July, from NE direction. The following days (17–19 July) were characterised by relatively stable, calm conditions – wind speed rarely exceeded 6 m/s. In the last days of July, wind speed increased, and on 31 July it exceeded 8 m/s (direction N and NW). Calm anemometric conditions occurred in August. Wind speed rarely exceeded 5 m/s, and the calm conditions were relatively common in comparison to other years. The wind

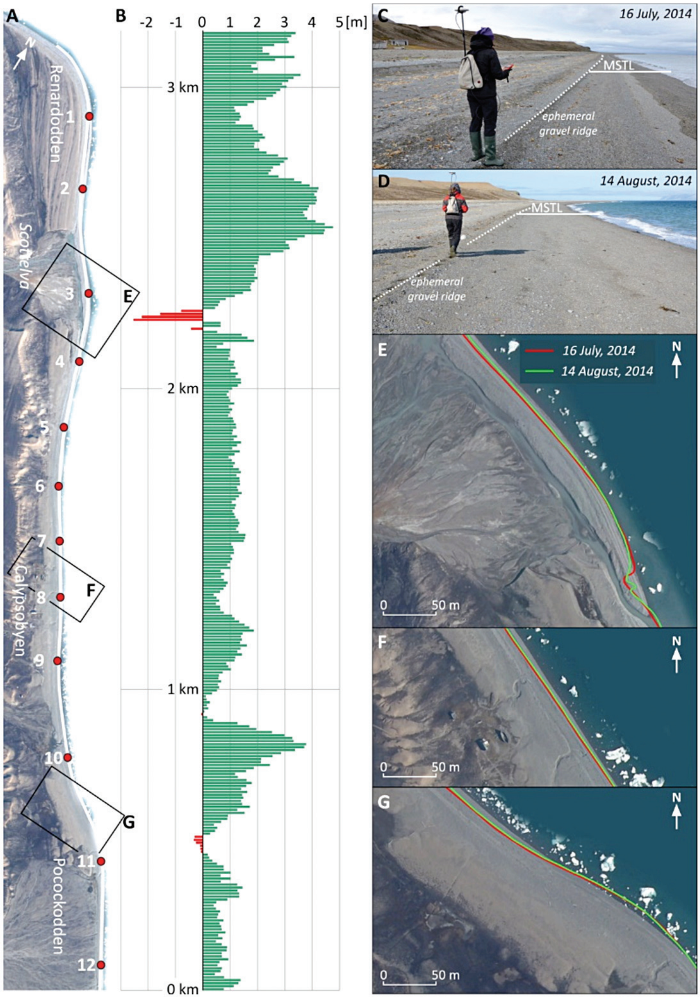

Fig. 6. Calypsostranda: (**A**) location of measurement coast area – white line after Orthophotomap, air photo from 2011, Norwegian Polar Institute, (**B**) shoreline changes between Skilvika and Pocockodden between 16 July and 14 August 2014 – Digital Shoreline Analysis Tool (DSAS) processing, (**C** and **D**) GPS measurement in 16 July and 14 August 2014; MSTL – maximum spring tidal level, and (**E**–**G**) – shoreline changes in selected area; background after Orthophotomap, air photo from 2011, Norwegian Polar Institute.

speed exceeded 8 m/s only on 10–14 August (wind from NE and E) and on 22 August (wind from W).

During the days where the photographs for the granulometric analyses were taken (26–28 August), variable wind conditions prevailed. On 26 August, wind from NE exceeded 6 m/s. On 27 August, before noon, speed of wind from NE, E, and SE rarely exceeded 3 m/s, and periods of calm occurred. During the afternoon, wind from E sporadically exceeded 2 m/s. In the evening, the wind direction changed to SE, and intensified to 6–7 m/s. This conditions persisted until the morning of 28 August. That evening, wind from S reached velocities of approximately 5 m/s (Fig. 5).

Wave conditions. — Wave conditions in Bellsund during the summer season of 2014 were highly variable (Fig. 5). Significant wave height (Hs) measured at distance 0.5 km from the shore varied from almost 0 to 0.57 m. The highest waves occurred on 16 and 12 July, as well as on 21 August. Low wave heights occurred on single days with weak winds and longer calm periods, namely on 14, 17, 28, 29 of July and 9, 10, 15 of August. Waves reaching the shore are transformed as a result of decreasing water-depth. Their length is reduced and height is increasing due to wave shoaling, therefore the waves observed at the shore are higher than those recorded offshore. Most of the time, the wave period (T) ranged from 4 to 7 s. Shorter wave periods were observed on days with strong wind from easterly directions (NE, E, SE). Longest wave periods (13 s on 10 August), were recorded during windless days when visible oceanic swell, undisturbed by wind waves, occurred.

High values of Hs (0.42 m) occurred on 12 July, during westerly wind, and the corresponding T amounted ~ 5 s (Fig. 5). The highest Hs (0.56 m) occurred on 16 July at maximum speeds of wind from NE and the shortest T of ~ 3 s. Relatively high values were reached by Hs on 31 July (0.32 m) when T was below 4 s. Also, the 18 August was characterised by relatively high Hs (0.31 m) and short T below 5 s. On 9–10 of August, Hs reached the lowest values below 0.02 m, and T increased to 13 s.

On the evening of 26 August, when the shore of Calypsostranda was reached by waves from E, and on the morning of 27 August, when the beach was reached by small wind waves from ESE, Hs was low (< 0.1 m) and T was 7–8 s. The oceanic swell waves were also observed. On the evening of 27 August, waves from ESE began to intensify. On the morning of 28 August, the beach was still reached by relatively large waves from ESE, and in the evening, in addition to wind waves from ESE, oceanic swell from N was recorded (Fig. 5).

Temporal variability of sediment on the shore. — Sediment grain size on the beach in Calypsobyen ranged from sand, through a cover of well sorted fine granule gravel, to medium-grained and coarse pebble gravel, and even small boulders with a diameter of a dozen centimetres (cobbles to gravels). Non-sorted sediment composed of pebbles to gravels with laminaria remnants from the nearshore (Fig. 2B) appeared on the beach on 12 July under waves characterized by high Hs whereas T showed average values. On 14 July, non-sorted gravel-sandy sediment was deposited on the beach. On 16 July, it was non-sorted fine and medium-grained gravel. With high values of Hs and low values of T, the wave was steep and short. It had no ability of abrasive impact on the bottom of the nearshore, and was not able to tear off the laminaria (Fig. 2C).

The portion of well sorted fine sediment increased with an increase in T and a decrease in Hs. On 10 August, at maximum values of T and low values of Hs, the beach was dominated by well sorted fine gravel (Fig. 2D).

Average values of T and high values of Hs on 18 August resulted in a weak sorting of beach sediments, where sediment grain size varied from very coarse sand to medium gravel (Fig. 2E). Hs was lower than that of 12 July, and therefore lower wave energy made it impossible to tear off laminaria from the nearshore.

Spatial variability of sediment between sites 1–12. — Sediment, in general, was the coarsest on Renardodden (sites 1 and 2). Gravels with diameters of 4–64 mm accounted for approximately 30% of the material covering the beach. The shapes of the cumulative frequency curves are similar, although at site 2 a higher variability of the sediment texture occurred between subsequent measurements. Only the curve of the last measurement is divergent, suggesting the appearance of a finer fraction on the evening of 28 August (Fig. 7; Supplement 1). The sediment becomes finer towards the south of the coast, with gravels with diameters below 4 mm becoming more frequent. At site 4, curves of all measurements are very similar, suggesting a lack of variability. South of the Scottelva mouth (site 4), sediment was similar to that at site 3 on 26 and 27 August. Differences occurred on 28 August, *i.e.* the finest sediment occurred in the morning, followed by coarser gravels. At sites 5 and 6, the variability of sediments on the beach was similar. On 26 and 28 August, fine sediment was deposited on the beach (with only few gravels > 64 mm), and on 27 August coarser gravels began to appear. At site 7, the sediment was finer compared to the northern sites, and coarsening was observed particularly on the evening of 27 August (Fig. 7; Supplement 1). In Calypsobyen (sites 8 and 9), the sediments were the finest. Here, sand accounted for up to 60% of the beach sediment and gravels > 4 mm accounted for only 11–17%. On 26 and 27 August, sediments were somewhat finer than those deposited at site 7. On 28 August, the beach was dominated by sand, although the granulometric software did not manage to interpret the finest sediments a similar problem appeared at sites 10 and 11 where sand deposited on the beach on the evening of 28 August was inaccurately interpreted by the software. At site 12, located southwards, where an outwash fan is subject to coastal erosion, the gravel fraction increased again with gravels > 4 mm exceeding 20%.

The analysis of cumulative frequency curves and grain-size parameters (average grain size and sorting) suggests a gradual decrease in mean grain diameter southwards from the mouth of Scottelva and a poor sediment sorting (Fig. 7; Supplement 1). In the measurement period, high variability of average grain size occurred at sites 1, 2, 5, 6, and 11, and low variability at sites 3, 4,

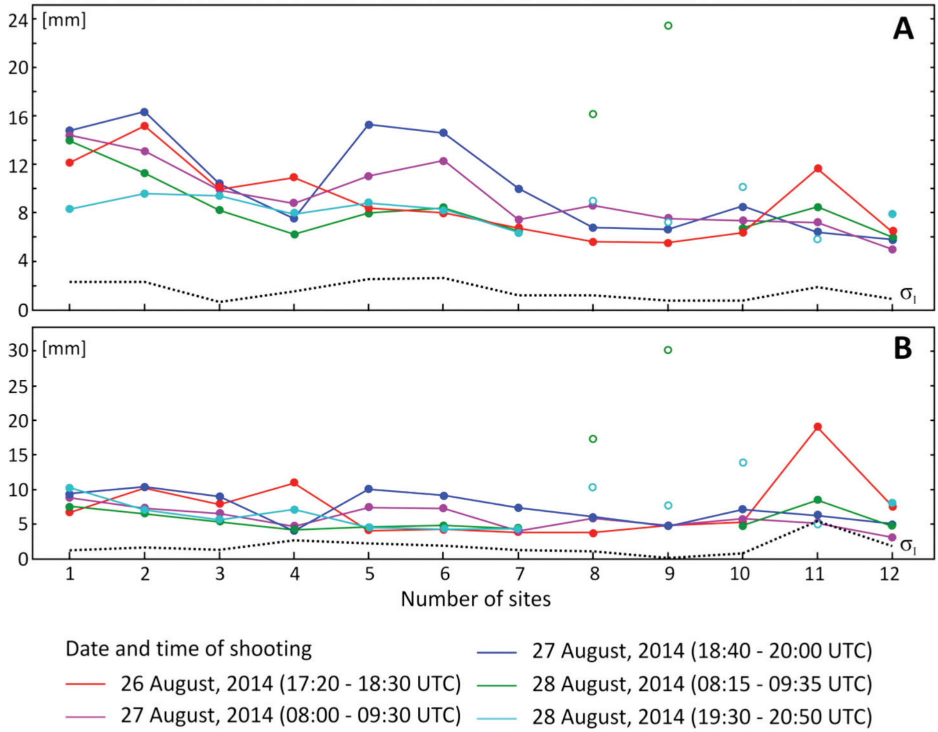

Fig. 7. Index of average grain size (**A**) and sorting (**B**); dotted line – standard deviation of the index at study sites; points without filling – incorrect result data Sedimetrics ® Digital Gravelometer.

and 7–10 (Fig. 7; Supplement 1). In the case of sediment sorting, a slight trend towards poor sorting was recorded southwards from the mouth of the Scottelva, with the exception of sites 11 and 12. In the measurement period, the greatest changes in sorting was determined at sites 4, 5, 11, and 12; the lowest at sites 1, 2, 8, and 9 (Fig. 7; Supplement 1).

Shoreline changes. — The first measurement of the shoreline position on 16 July 2014 was performed after several days of storm with dominant onshore waves from the E (Fig. 5). The ephemeral gravel ridge that developed was characterised by a concave profile on the seaward side, resulting from the abrasive wave activity (Fig. 6C). The next measurement (14 August 2014) was taken after a period of swell from W directions (Fig. 5). The developed ephemeral gravel ridge of this time was characterised by a convex profile on the seaward side, which indicated that material accumulated as the result of wave action (Fig. 6D). In general, advance of the shoreline was observed, averaging to 1.45 m for the studied section, with maxima at sites 3 (4.76 m) and 10 (3.76 m). Four zones of the shore analyses were clearly distinguished, *i.e.* (*i*) north of the mouth of

Scottelva between sites 1 and 3 with a considerable advance ~ 2.5 m, (*ii*) south of the mouth of Scottelva between sites 4 and 9 with advance averaging ~ 1 m, (*iii*) at site 10 with advance averaging ~ 2 m, and (*iv*) between sites 11 and 12 with advance averaging ~ 0.8 m (Fig. 6). Some zones of shoreline retreat were also observed. They averaged to 0.76 m for the studied section, with a maximum retreat of 3.17 m. They occurred (*i*) between sites 3 and 4 as a result of the southward migration of the Scottelva mouth, (*ii*) on a pronival stream (between sites 9 and 10), and (*iii*) at site 11 (Fig. 6).

Discussion

Anemometric conditions of wave climate. — Most researchers analyse the coastal changes on annual time scales (Zagórski 2011; Sessford *et al*. 2015a). Research carried out on the shore of Calypsostranda in 2014, however, shows that a short wave episode can significantly change the sediment texture in the intertidal zone even during one day (Figs 7 and 8; Supplement 1).

On the shore of Calypsostranda, wind waves are the most efficient in changing the beach sediment characteristics. They generate short waves with high energy, reaching more than 1.5 m in height, usually approaching the coast obliquely, causing a strong longshore drift towards the NW. Transport of sediment in the intertidal zone, however, occurs particularly through the oscillating movement of waves towards the land and in accordance with the direction of wave impact. During the field season 2014, winds from the east sector did not dominate (in total they constituted less than 40%), and did not reach high speeds. The average value from the entire season for wind from NE amounted to 4.5 m/s, and for N and SE the values are even lower. Therefore, the maximum wave height from the E only slightly exceeded 0.5 m. During strong and long-lasting wind from the E, high and short wind waves with a very short period (3 seconds) reaches the shore of Calypsostranda at an angle of approximately 90° (Fig 5). They have a low ability of abrasive impact on the bottom of the nearshore (Fig. 8A). However, observations show that they wash sand from the intertidal zone, but are not able to remove coarser sediments (Fig. 2C). If wave height is sufficiently high to tear off laminaria from deeper waters in the nearshore, they are also transported to the shore. Such waves appeared, for example, on 16 July and 28 August 2014, and caused deposition of poorly sorted sand, gravel and few small boulders on the beach.

During strong winds from the W sector, waves altered by diffraction reach the Calypsostranda shore (Fig. 8B). These waves are quite high, considering the Calypsostranda coast, and long, however with a shorter period than swell, and have a great ability of abrasive impact on the sea floor. They remove the seaweed from the nearshore, and wash out sand and gravel from the tidal zone

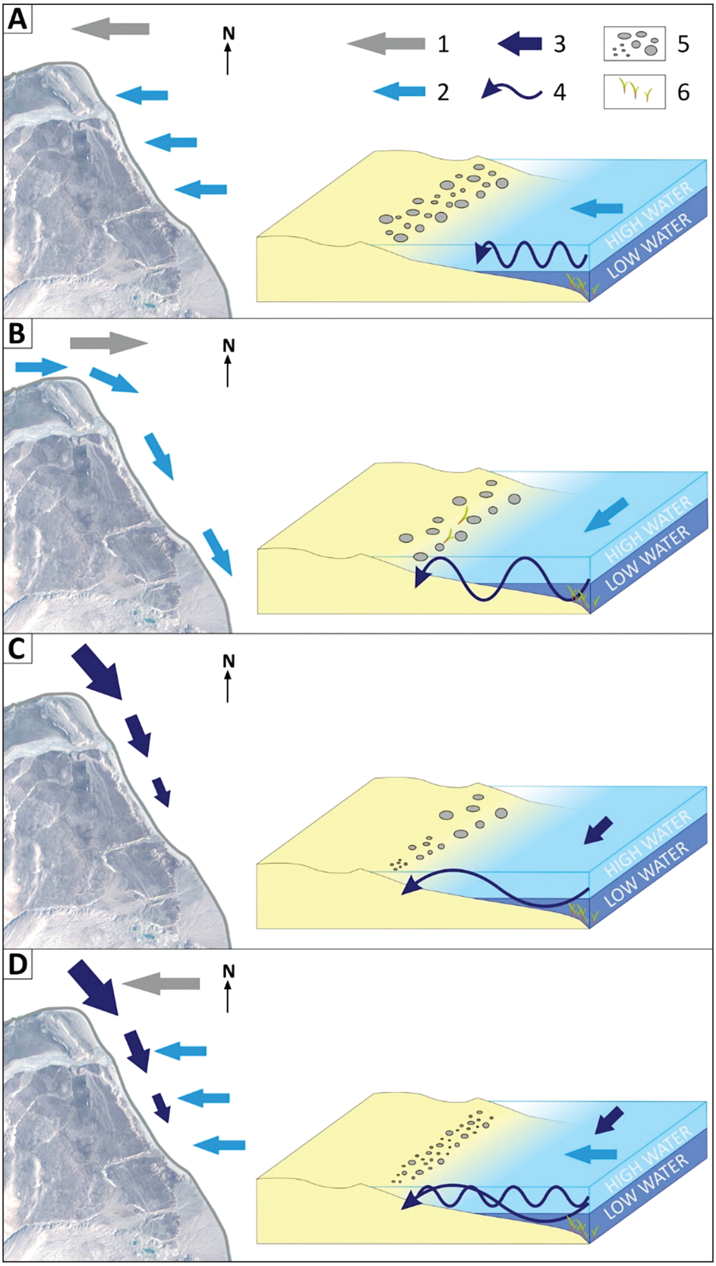

Fig. 8. Response of the shore zone and directions of sediment movement depending on the wave direction and wave type (background after Orthophotomap, air photo from 2011, Norwegian Polar Institute): **A** – eastern wind, high waves with short period, **B** – western wind, quite high and long waves, **C** – low waves of oceanic swell from N and NW with very long period, and **D** – eastern wind and swell from N and NW simultaneously. Legend: 1 – wind direction, 2 – wind wave direction, 3 – swell direction, 4 – depth of the wave and its ability of abrasive impact on the bottom of the nearshore, 5 – grain size of material occurring in tidal zone, 6 – seaweeds.

(Fig. 2B). They also cause movement of finer grained sediments along the shore towards the S.

The shore of Calypsostranda is also reached by low waves of oceanic swell from the N and NW (Fig. 8C). Oceanic swell reaches the shore of Calypsostranda indirectly, and was previously believed to be of low importance (Zagórski 2011; Zagórski *et al*. 2013). Its effect is the greatest for winds from the W where Calypsostranda is sheltered by the mountains. Oceanic wind waves freely enter Bellsund, however, they are subject to diffraction and gradual decline due to subsequent capes distributed along its southern shore. The shore of Skilvika is the one most susceptible to their effects. The research conducted in 2014 indicated that although the shore of Calypsostranda is sheltered by Renardodden, the swell close to the shore could reach a significant height, as the result of waves entering shallower coastal waters and as such their impact on the shore is considerable (Tarbuck and Lutgens 1998). Swell waves wash out the finest fractions of sediments from among coarser gravels, and move them to the south. Sediment thrown on the shore during episodes of high wind waves is also re-distributed by swell along the shore afterwards. Swell reaching the shore of Calypsostranda has a direction similar to waves caused by W winds. However, the swell waves are lower and have a very long period exceeding a dozen seconds (Figs 5 and 8C). They can wash out sand from the nearshore, and relocate it into the tidal zone, causing segregation of the sediment and transport of finer fractions along the shore in accordance with the direction of attack of the oceanic wave, *i.e*. in the S direction (Fig. 2D).

Waves of different origin sometimes reach the shore of Calypsostranda from various directions simultaneously. Swell arrives from NW, and wind waves from the E sector (Fig. 8D). In such situations, sand washed away from the nearshore is present in the tidal zone (Fig. 2E). Inconsiderable, secondary wind waves have no influence on the direction of sediment transport in the shore zone, even if waves approach from a direction opposite to that of the swell.

Factors controlling shore development. — In contrast to the shore of Calypsostranda which is shaped mainly by wind waves, Zagórski *et al*. (2015) showed that wind waves have a limited impact on the shore of Isbjørnhamna (bay in the Hornsund), which is shaped mainly by swell waves. Changes of the Isbjørnhamna shoreline are also dependent on the frequency and intensity of storms during ice free periods, the configuration of the bottom of the bay, and the exposure and resistance of the shore to coastal erosion. Erosional or accumulation can vary from season to season, depending on the prevailing conditions. The diversity of the exposure of the coast of Spitsbergen to the prevailing direction of waves makes it difficult to compare individual research areas. Zagórski *et al*. (2015) indicated waves (particularly swell) as the main cause of Isbjørnhamna shore erosion, while Sessford *et al*. (2015a) showed a slight impact of waves on the coast inside the Isfjord. Seemingly, these conclusions are contradictory. However, they suggest differences in the impact of waves on particular parts of the coast. Wojtysiak *et al*. (2018) indicated that the dominant direction of the swell at the entrances to the fjords of the west coast of Spitsbergen is from the SW. The effect of this unimodal direction of swell-wave impact on the coast is that the northern coasts (*e.g*. Isbjørnhamna) are more vulnerable to wave erosion, and the southern coasts (*e.g*. Calypsostranda) and the inner parts of the fjords are less. This view is confirmed by detailed research conducted in Hornsund (Herman *et al*. 2019).

Strzelecki *et al*. (2017b) paid attention to the role of permafrost that binds sediments and releases ephemeric streams. Permafrost thaw and intensification of periglacial processes on local slopes supply large amounts of sediment to the shore zone. Based on research in Petuniabukta (the northern branch of Isfjord), Strzelecki *et al*. (2017a) linked shoreline changes with episodic sediment delivery from land, *e.g*. from snow-melt and permafrost catchments. The research conducted in Calypsostranda seems to confirm the importance of these factors. The mouth of Scottelva currently inhibits the transport of fine grained sediment (washed out from among coarser gravels in the N part of Calypsostranda) rather than delivery of sediment to the shore (Fig. 6). However, according to Zagórski *et al*. (2008a), large amounts of terrigenous sediments were removed from the catchment by proglacial waters of Scottelva and supplied to the shore zone after a period of intense precipitation in 2002.

Coastal variability of sediments on the Calypsostranda shore. — Considering the spatial distribution of sediment, the coarsest sediment is deposited in the northern part of the shore of Calypsostranda (Fig. 7; Supplement 1). This part of the shore is located nearest to the main source of sediment supply, namely the eroding cliffs in Skilvka (Fig. 3). Moreover, it is exposed to the strongest effect of swell waves, washing out the finest fractions of sediments from among coarser gravels. In the area of the mouth of Scottelva, where the longshore bedload stream is disturbed by the river stream flowing into the sea, sediment deposited on the shore is enriched in fines (Fig. 7; Supplement 1).

In the 2014 season, the supply of terrigenous material, especially from the Scottelva Catchment, was not significant. The recorded values of flows do not indicate the presence of favorable conditions to the intensive supply of material (Fig. 3). Such events do not occur every year but are of episodic nature. High flows are important if we consider the amount of the material supplied to the shore zone, its along-shore redistribution as well as advance of shoreline (Krawczyk and Bartoszewski 2008; Zagórski 2011; Zagórski *et al*. 2013).

The finest sediment is deposited along the beach in the middle part of Calypsostranda. At this location, the supply of coarser sediment is limited due to the large distance from the sediment sources (such as Skilvika, Scottelva).

In addition, the Scottelva estuary inhibits longshore transport of material from north-west and there are no other sediment sources in this part of shore (Fig. 7; Supplement 1). In conditions of swell, fine sediment from the nearshore is discharged to the shore.

In the southern section of the shore, in the Pocockodden region, an inactive outwash fan of the Renardbreen is subject to weathering. Relatively fine local sediment and flat gravels originating from the erosion of the outwash plain are deposited on the shore.

Conclusions

Wind waves have the greatest effect on the shore of Calypsostranda. They contribute to erosion and redeposition of sediment from the nearshore and the intertidal zone. Maximum values of significant wave height at the shore of Calypsostranda are recorded during maximum speeds of NE wind. Also during strong winds from the W, quite high and long waves changed by diffraction reach the Calypsostranda shore. They have a great ability of abrasive impact on the sea floor, *i.e.* remove the seaweed from the nearshore, and wash out sand and gravel from the tidal zone. Oceanic swell waves reaching the shore of Calypsostranda (waves with a long period) have a great ability of abrasive impact on the sea floor of nearshore as well as contributes to better sorting of sediment deposited on the shore through washing it out from among gravels, and transporting the finest fraction to the south.

The local wave climate including wind and swell waves as well as resulting of longshore drift plays a central role in the development of the high-energy shores of the southern Bellsund. Due to the 20 km wide opening of the Bellsund to the Greenland Sea, open sea waves impact the open sea coast, but the southern shores of the Bellsund are also reached by diffracted waves, particularly in the case of swell. These shores can thus be regarded as transitional between high and low energy coasts, where erosional coasts prevail in genetic terms.

One important observation made during this study was that grain-size distribution along the shore can be significantly changed during one tidal cycle. The scale of modification depends not only on wave height and its period but also on the direction of wave impact.

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P.Z., K.M., M.M., and J.R. created the concept, designed the study, and wrote this manuscript. M.M. performed grain analysis in Sedimetrics ® Digital Gravelometer software. A.H. performed wave and tide analysis. P.Z. and K.M. performed wind conditions and hydrological analysis, prepared the figures, and cartographic and graphic sediment. Ł.P. performed shoreline change analysis. P.Z., K.M., M.M., J.R., A.H., M.J. and Ł.P. collected field data.

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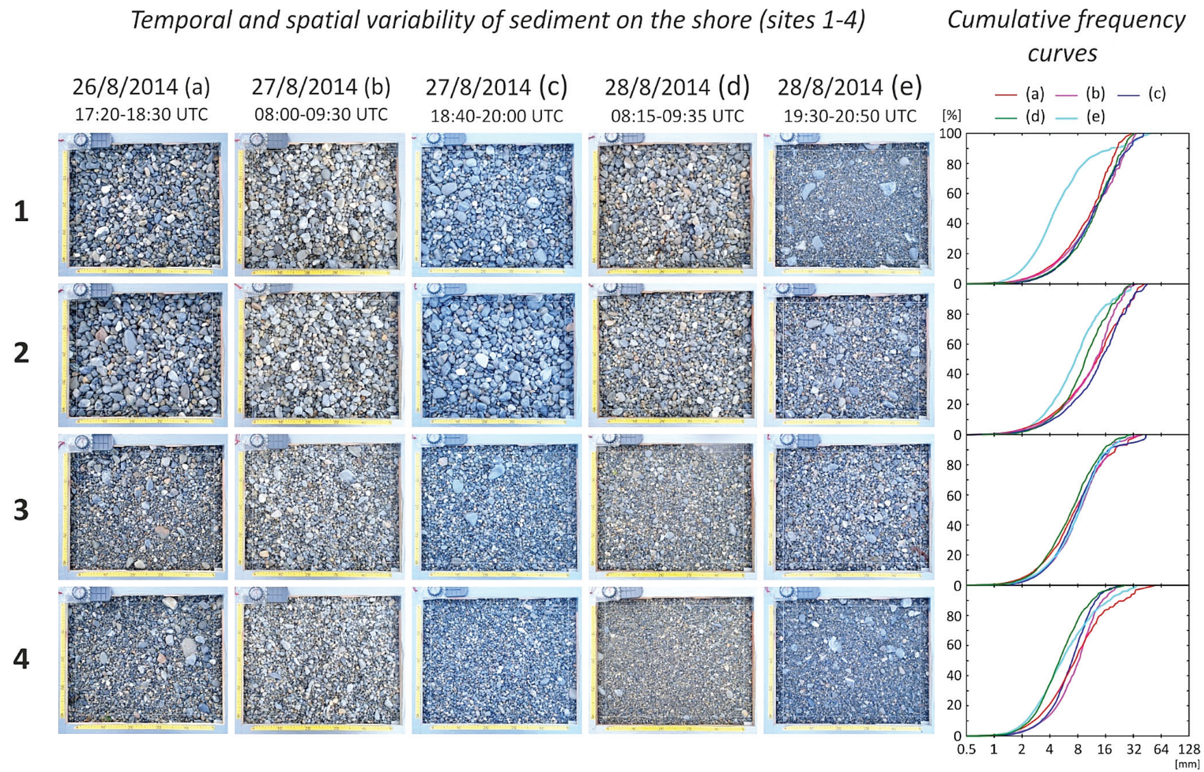
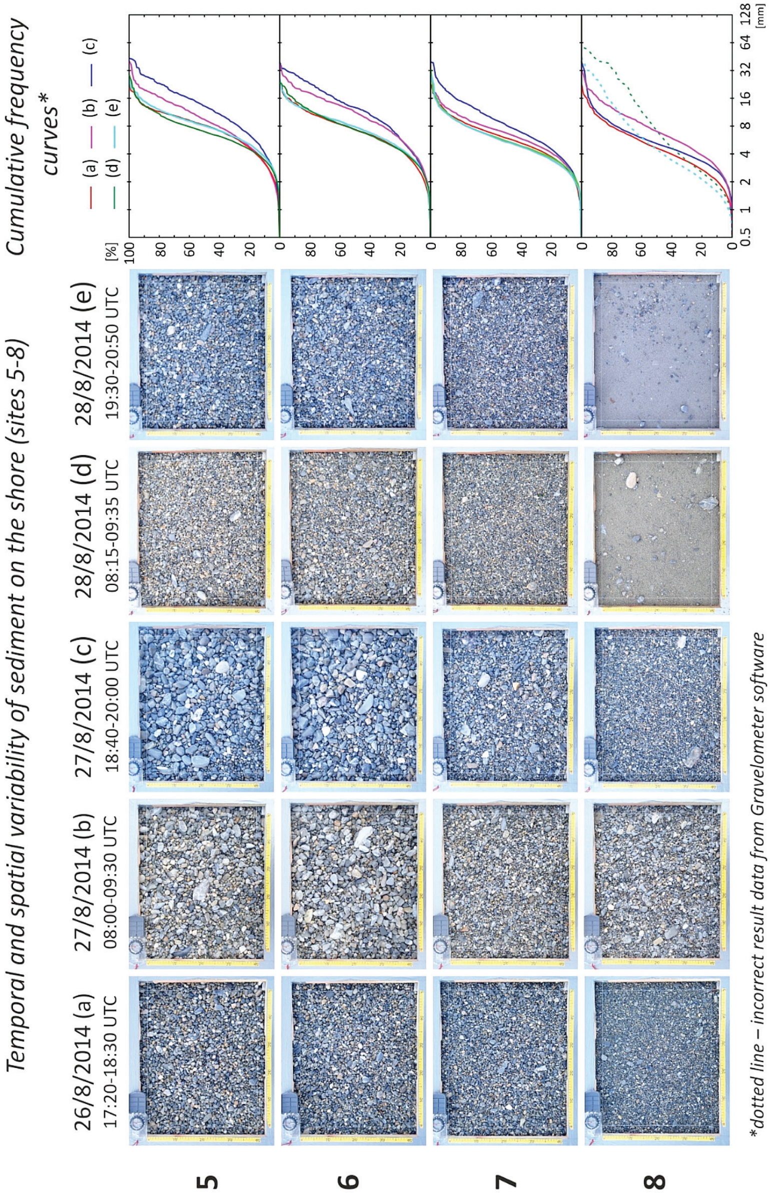
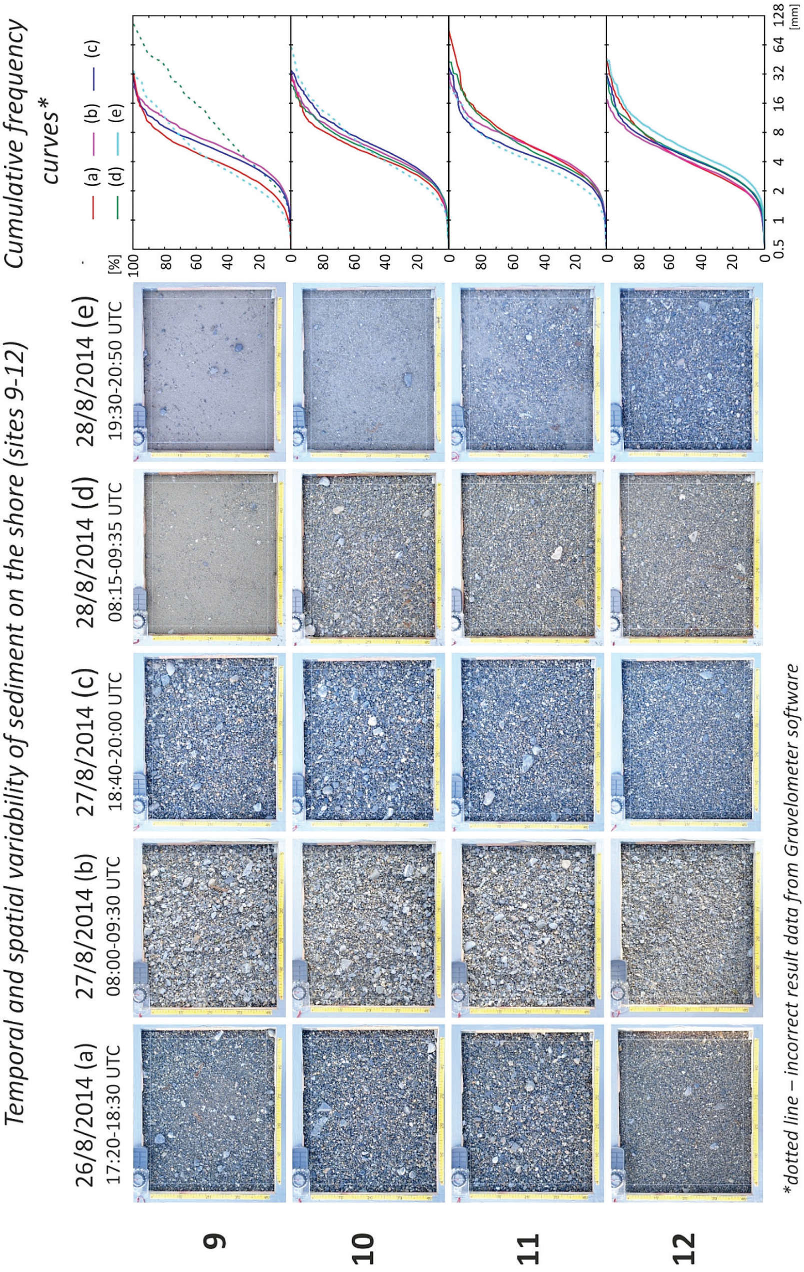
Supplement 1

Temporal and spatial variability of sediment on the shore (sites 1–12) and cumulative frequency curves.




Temporal and spatial variability of sediment on the shore (sites 5-8)
26/8/2014 (a)
17:20-18:30 UTC
27/8/2014 (b)
08:00-09:30 UTC
27/8/2014 (c)
18:40-20:00 UTC
28/8/2014 (d)
08:15-09:35 UTC
28/8/2014 (e)
19:30-20:50 UTC
Cumulative frequency curves*
(a) (b) (c) (d) (e)
[%] 100 80 60 40 20 0
0.5 1 2 4 8 16 32 64 128 [mm]
5
6
7
8
*dotted line – incorrect result data from Gravelometer software


Temporal and spatial variability of sediment on the shore (sites 9-12)
Cumulative frequency curves*
26/8/2014 (a)
17:20-18:30 UTC
27/8/2014 (b)
08:00-09:30 UTC
27/8/2014 (c)
18:40-20:00 UTC
28/8/2014 (d)
08:15-09:35 UTC
28/8/2014 (e)
19:30-20:50 UTC
9
10
11
12
(a) (b) (c) (d) (e)
[%]
100 80 60 40 20 0
0.5 1 2 4 8 16 32 64 128 [mm]
*dotted line – incorrect result data from Gravelometer software